



# *Orbiter Entry Aerothermodynamics*

## *Practical Engineering and Applied Research*

**Charles H. Campbell**

**Orbiter Entry Boundary Layer Transition Flight Experiment**

**Principal Investigator**

**Applied Aerosciences and CFD Branch**

**NASA Johnson Space Center, Houston, TX**

**May 12th, 2009**

**Invited Presentation at Stanford University**

**Mechanical Engineering Department**

**Fluid Mechanics Seminar**

**STS-114 Launch on July 26<sup>th</sup>, 2005**





# Orbiter Return to Flight Aeroheating

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- **Outline**

- **Organization of the Orbiter Entry Aeroheating Working Group**
- **Overview of the Principal RTF Aeroheating Tools Utilized for Tile Damage Assessment**
- **Description of the Integrated Tile Damage Assessment Team Analyses Process**
- **Space Shuttle Flight Support Process**
- **JSC Applied Aerosciences and CFD Branch Applied Research Interests**

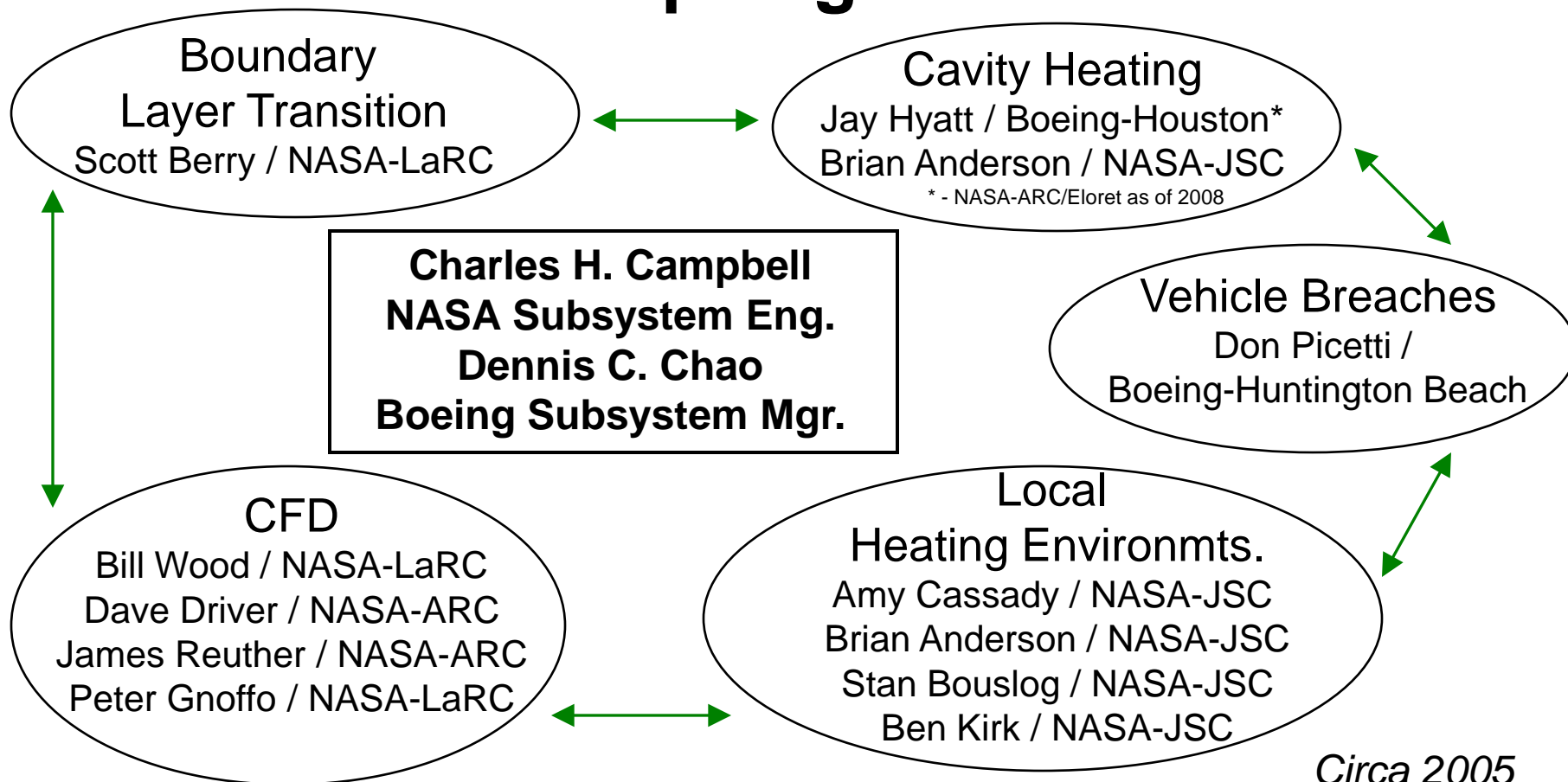


# Orbiter Return to Flight Aeroheating



## Orbiter Entry Aeroheating Working Group Organization

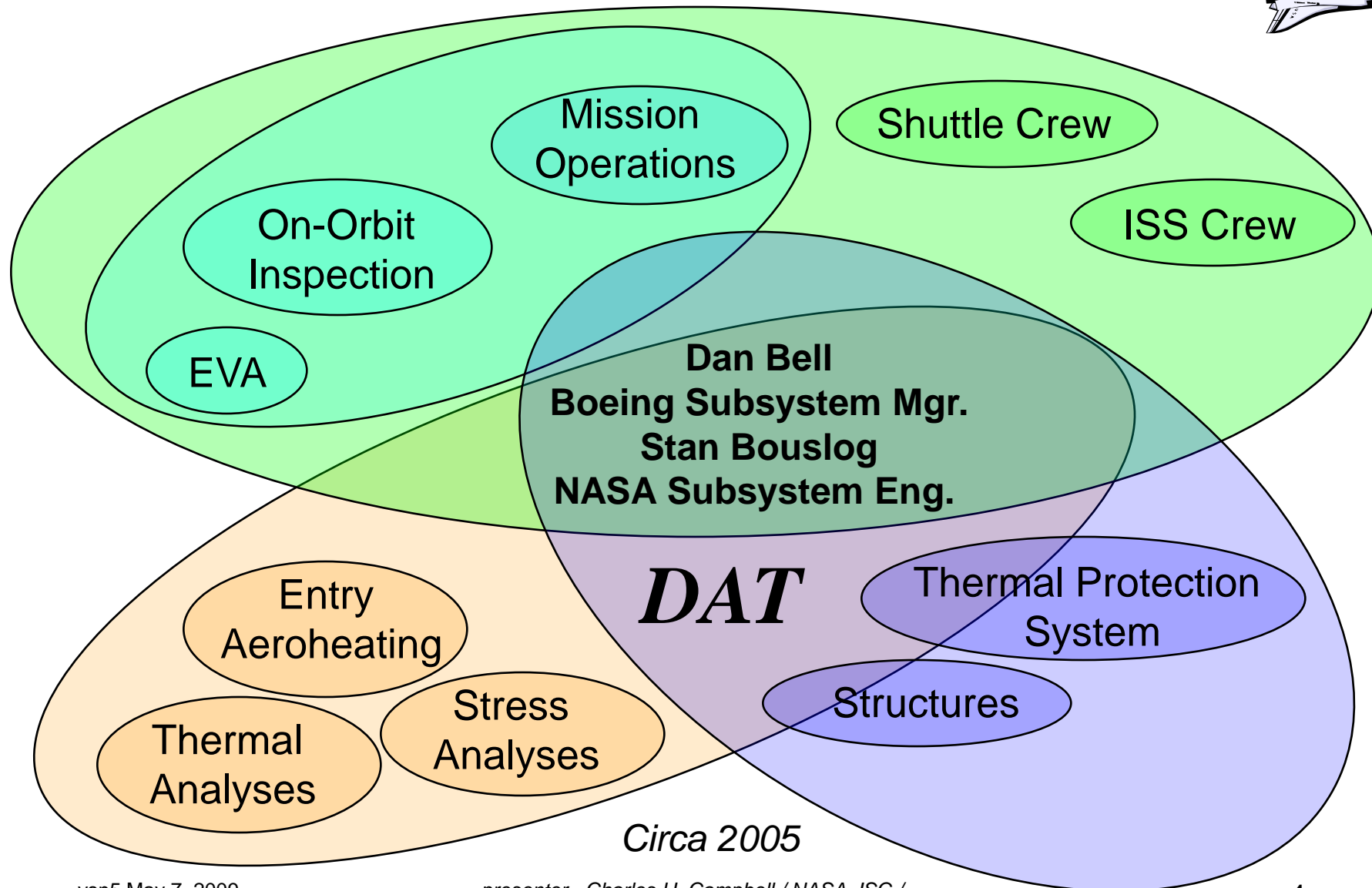
Ref: Campbell et al, AIAA-2006-2917



*Circa 2005*



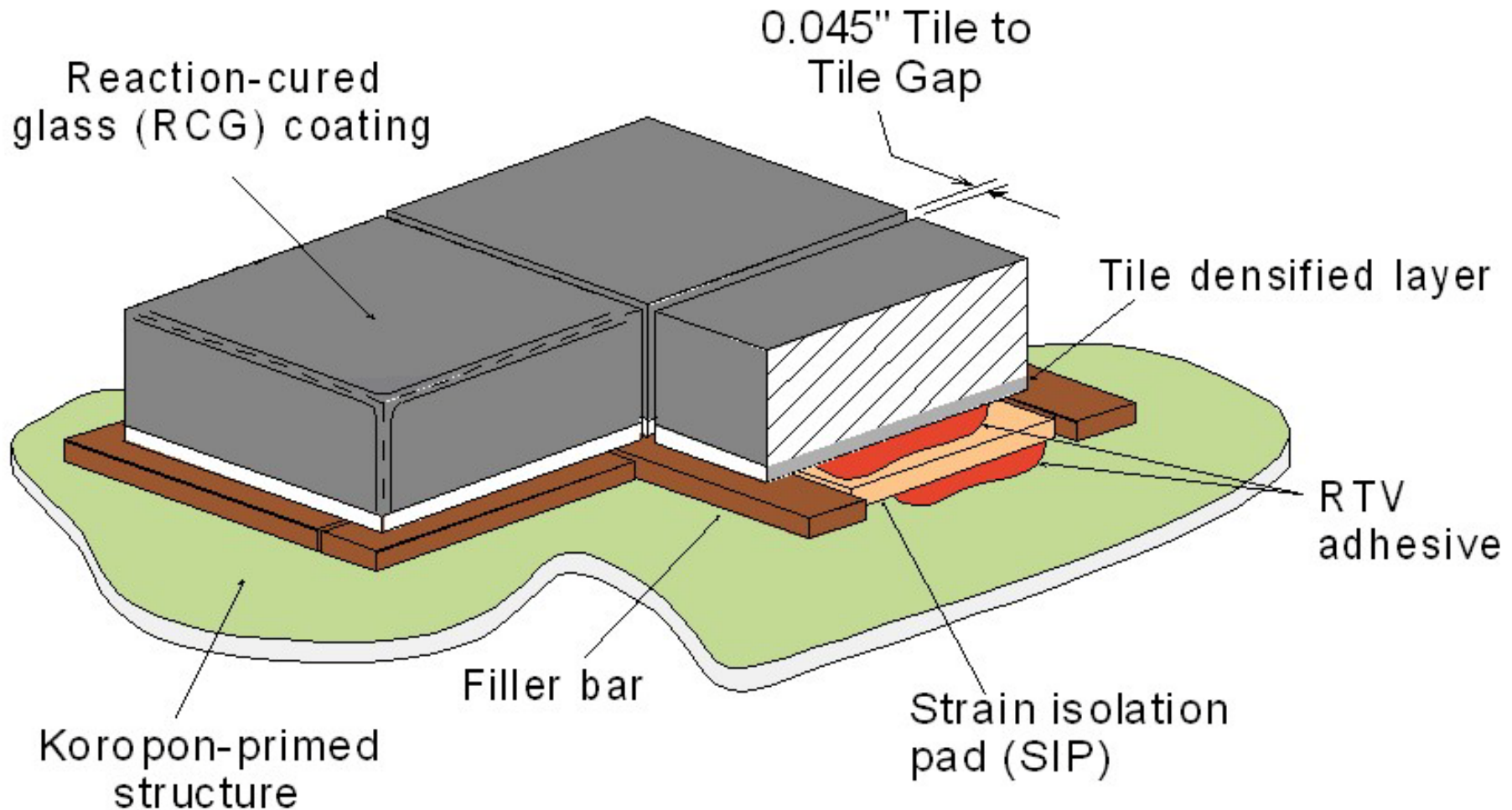
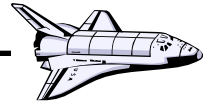
# Tile Damage Assessment Team



*Circa 2005*



# Tile System Description



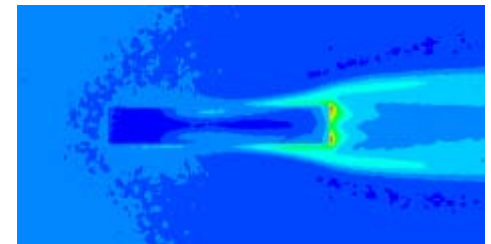


# Orbiter Return to Flight Aeroheating



- **Principal Aeroheating Tools for DAT**
  - **XF0002 / Nominal Convective Heating**
    - Utilizes simplified heating methods for > 2000 OML locations
      - Phenomenology: Temperature based heat transfer coefficient
    - Developed during Orbiter DDT&E
    - Calibrated to Orbiter flight data
  - **Catalytic Heating / Uncoated Tile catalycity**
    - Based on preliminary arc-jet data
    - Utilizes a simple bump factor relationship
  - **Cavity Heating / Damaged tile cavity heating**
    - Updates for laminar effects based on wind tunnel data
      - Phenomenology: Temperature based heat transfer coefficient
    - Historical turbulent correlation based on extant experimental data
    - Methodology Utilizes Engineering correlations
      - Shallow Cavity (new)
      - Everhart Cavity (new)
      - Closed Cavity (new)
      - Turbulent Cavity (historical Boeing method)

NASA LaRC Mach 10  
Thermographic Phosphor Cavity Heating



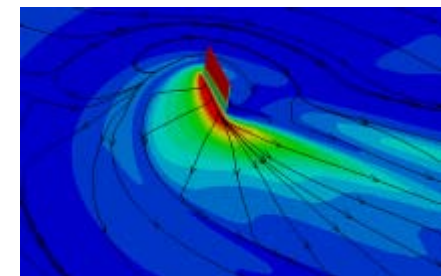
Ref: Everhart et al, AIAA-2006-185



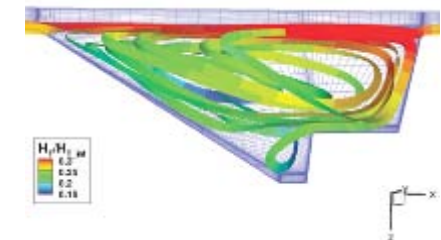
# Orbiter Return to Flight Aeroheating



Protrusion CFD Simulation



Flight Cavity CFD Simulation



- **Principal Aeroheating Tools for DAT (cont'd)**
  - **Rapid Assessment CFD**
    - Utilizes DPLR and LAURA
      - Nonequilibrium chemistry, Navier-Stokes solvers
    - Calibrated to available cavity experimental data
    - Leverages multiple capabilities to satisfy efficiency needs
      - Automated grid generation
      - Repository of Smooth Baseline Orbiter solutions
      - Sub-zone decomposition to solve local damage region
      - NAS Columbia system for rapid turn-around
  - **Boundary Layer Transition**
    - Methodologies developed for Protuberances and Cavities
    - Principal data sets from NASA-LaRC Mach 6 and 10 air tunnels
      - Complementary data from AEDC MH-11 Orbiter test (ca. 1993) and CUBRC MH-13 Orbiter test
      - Correlations established for wind tunnel data and calibrated to available Orbiter flight data
    - Relies on Boundary Layer Properties tool to provide edge conditions in flight envelope
      - Flight Envelope and Wind Tunnel databases established with DPLR and LAURA Nonequilibrium N.S.

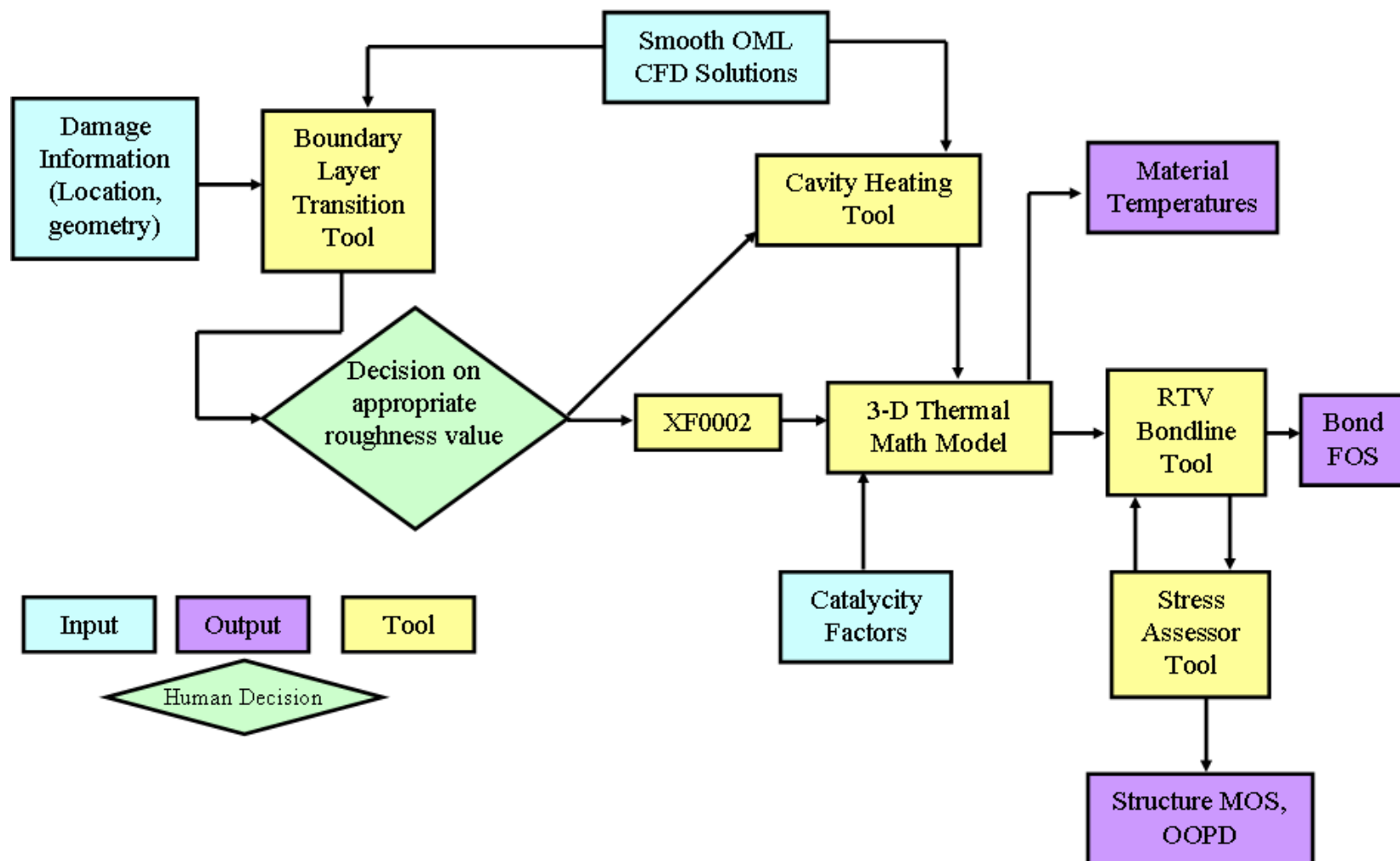
Ref: Palmer et al, AIAA-2007-4254  
Pulsonetti et al, AIAA-2005-4679



# Tile Damage Assessment Team



## Flight Support Process





# STS-114 Damage Assessment



*Assessments Required*  
4 windward sites  
2 protruding gap fillers  
1 blanket (leeside)



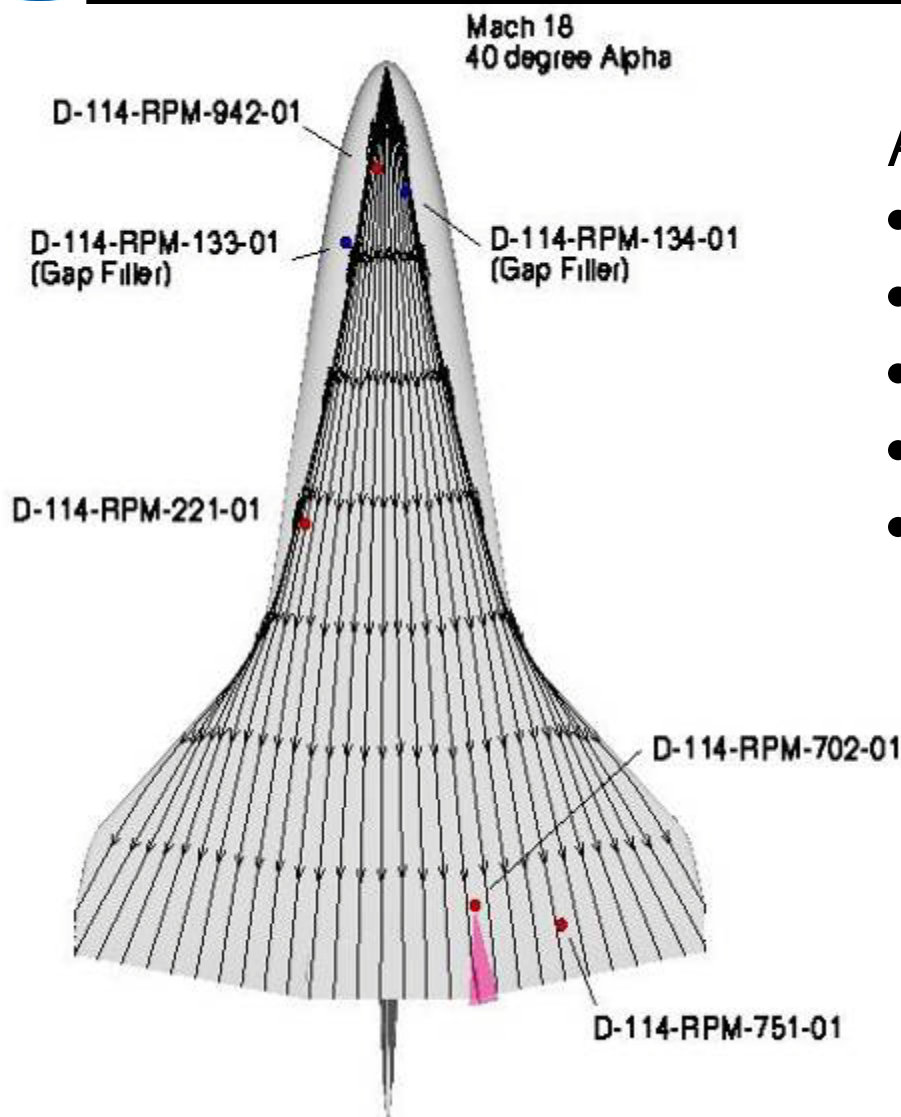
# Damage Assessment Since STS-114



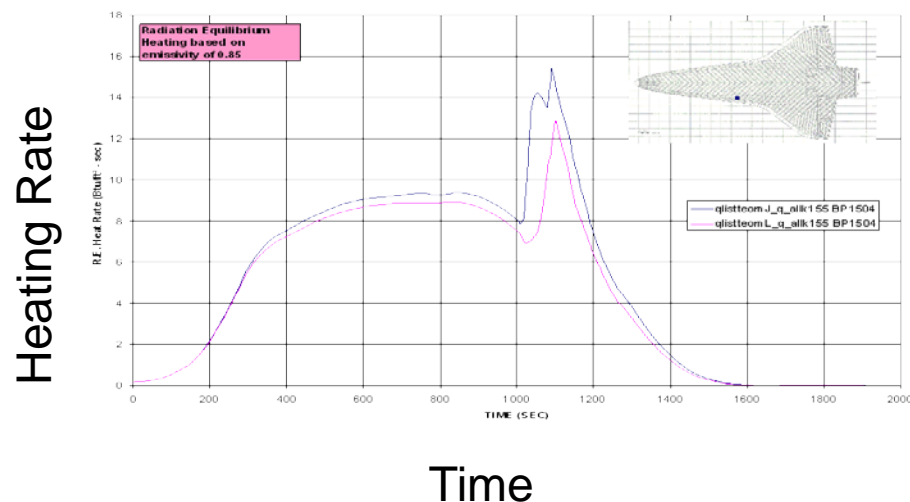
<b>STS Mission</b>	<b>Launch</b>	<b>Entry</b>	<b>Total Damage Sites Examined by Damage Assessment Team</b>
<b>STS-114</b>	July 26, 2005	August 9, 2005	49
<b>STS-121</b>	July 4, 2006	July 17, 2006	13
<b>STS-115</b>	September 9, 2006	September 21, 2006	28
<b>STS-116</b>	December 9, 2006	December 22, 2006	10
<b>STS-117</b>	June 8, 2007	June 22, 2007	11
<b>STS-118</b>	August 8, 2007	August 21, 2007	25
<b>STS-120</b>	October 23, 2007	November 7, 2007	14
<b>STS-122</b>	February 7, 2008	February 20, 2008	17
<b>STS-123</b>	March 10, 2008	March 26, 2008	20
<b>STS-124</b>	May 31, 2008	June 14, 2008	14
<b>STS-126</b>	November 14, 2008	November 30, 2008	13
<b>STS-119</b>	March 15, 2009	March 28, 2009	10



# STS-114 Damage Assessment



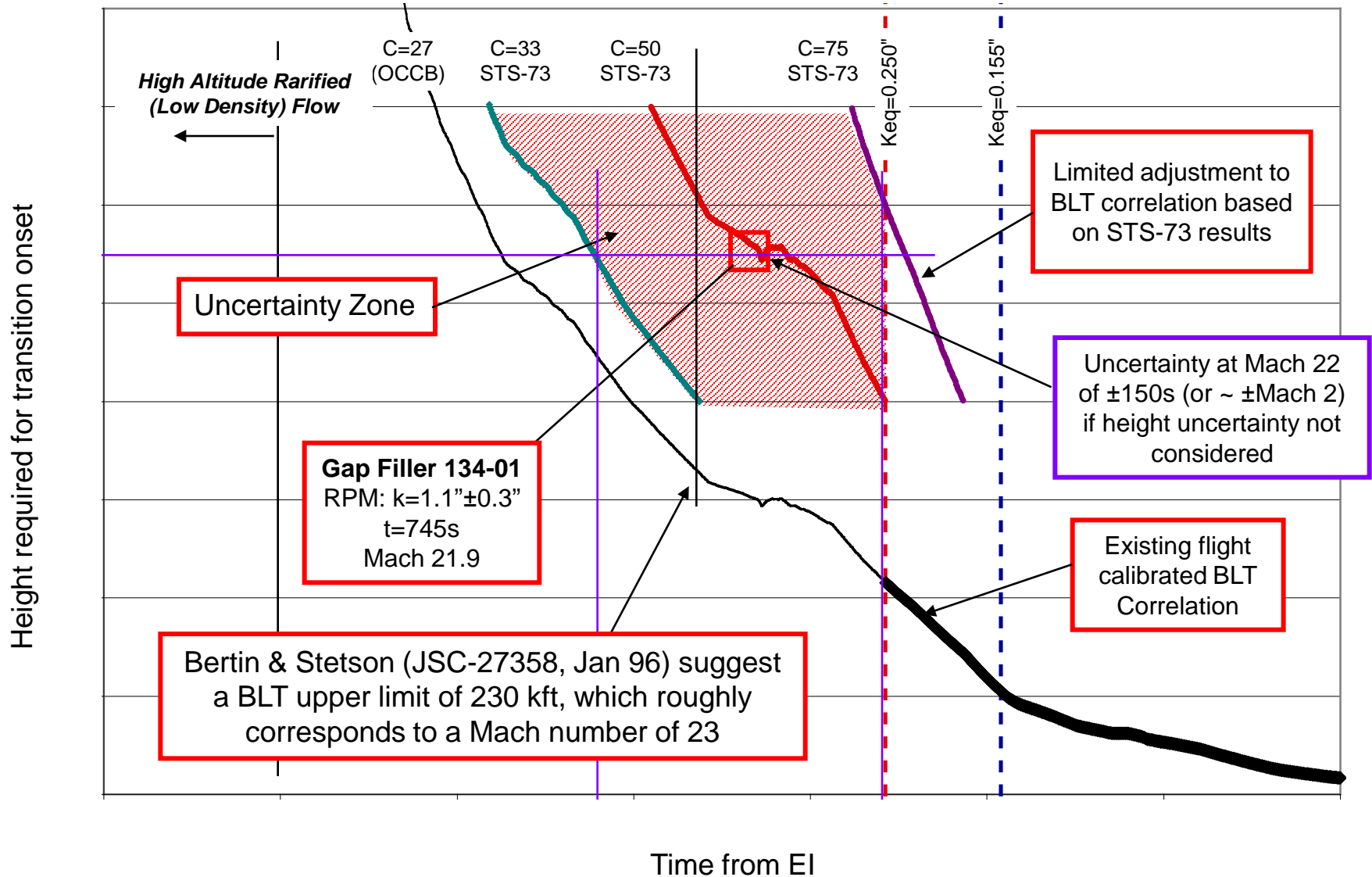
- ## Aeroheating Team Report Info
- Windward view (to left)
  - Turbulent Influence zone
  - BLT Predictions for each site
  - Reference Heating
  - Cavity Heating summary





# STS-114 Gap Filler Assessment

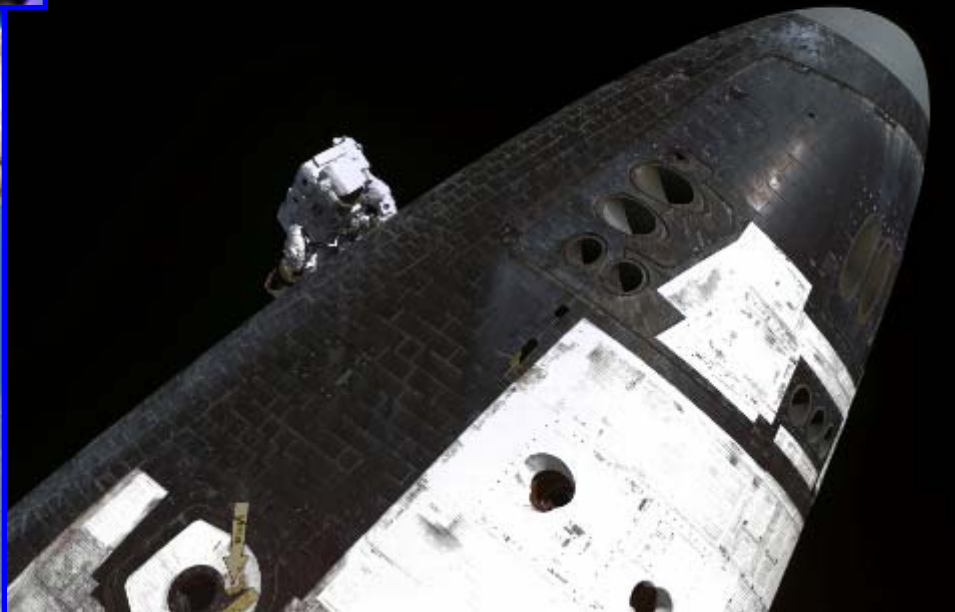
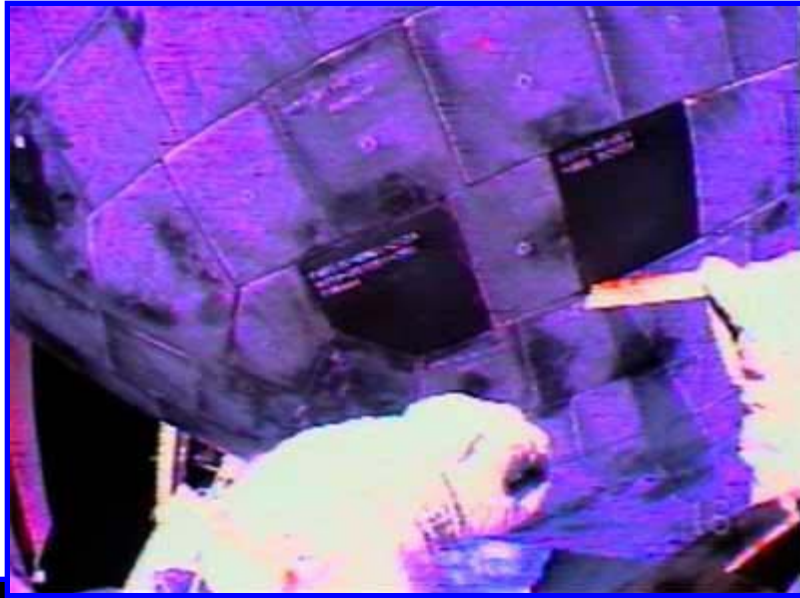
$$K=C(\delta)/(R\theta/M\delta)$$





# STS-114 Gap Filler Removal

Stephen R. Robinson  
and Soichi Noguchi  
performed the first ever  
on-orbit TPS repair  
on August 3, 2005



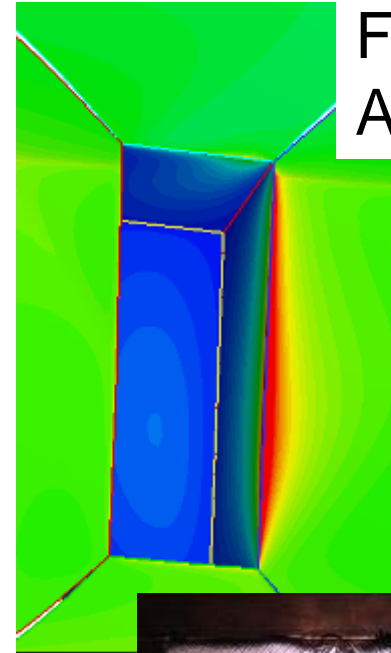


# STS-117 OMS Pod Blanket Repair

On-Orbit,  
prior to repair



Flight CFD  
Assessment



Danny Olivas  
performed the first ever  
on-orbit OMS Pod repair  
on June 15, 2007





## Stephen Robinson portrait after STS-114 Gap Filler Repair

vsn5 May 7, 2009

*presenter - Charles H. Campbell / NASA JSC /  
charles.h.campbell@nasa.gov*

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## Danny Olivas self-portrait after STS-117 OMS Pod Blanket Repair

vsn5 May 7, 2009

presenter - Charles H. Campbell / NASA JSC /  
[charles.h.campbell@nasa.gov](mailto:charles.h.campbell@nasa.gov)

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# JSC Aerosciences Branch

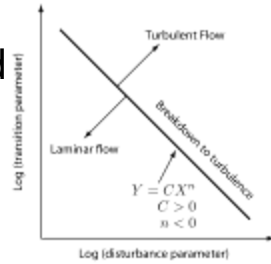
## Current Applied Research Interests

- Boundary Layer Transition Prediction
  - Engineering Correlations (NASA)
  - Stability modeling (University of Minnesota/Candler, Johnson)
- Quiet Hypersonic Experimental Capabilities
  - Purdue Mach 6 Quiet Tunnel (Schneider, et al)
- Hypersonic wind tunnel non-intrusive measurement
  - Planar Induced Fluorescence (LaRC / Danehy, et al.)
- Roughness Induced Augmented Heating
  - Crew Exploration Vehicle (CEV) Heat Shield (JSC / Amar, et al.
- Hypersonic Expansion Tunnels
  - CUBRC LENS-XX (Holden, et al.)
- Other topics related to aerosciences



# Discrete Roughness BLT

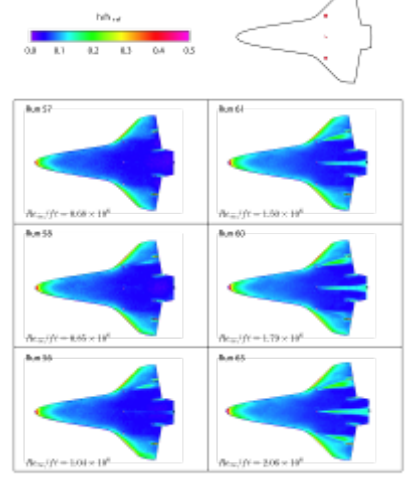
- Develop engineering tool for rapid Orbiter transition prediction. A generalized correlation approach was implemented.



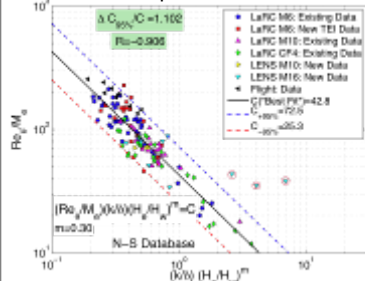
Model in LaRC 20-Inch Mach 6



Phosphor Thermography Data

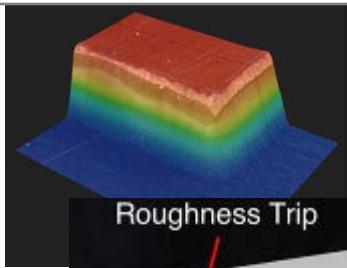


Sample Correlation



## References:

- King R.A., et al., JSC EG-SS-07-07, 2007.
- McGinley, C.B., et al., AIAA 2006-2921.
- Liechty, D.S., et al., NASA/TM 2006-214306.
- Cassady, A.M., et al., NASA/TP 2007-214758.
- King, R.A., et al., NASA/TM 2008-215103.



Rudy King, Mike Kegerise

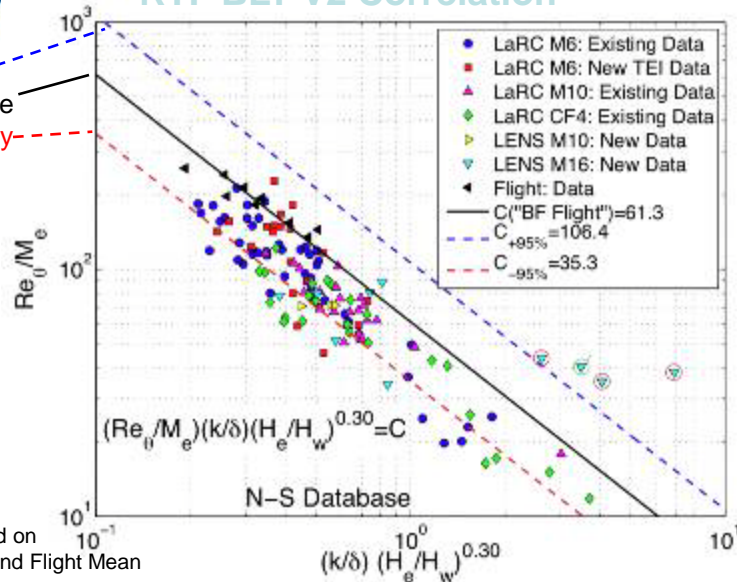


- Future work supported by Hypersonics Program in the Fundamental Aeronautics Program / ARMD.
- Investigate effects of discrete roughness on stability & transition of Zero Pressure Gradient BL in a Mach 3.5 quiet tunnel.
  - Objective is to understand the underlying physics leading to BLT that may ultimately lead to improved physics-based correlation methodologies.
  - Acquire off-surface measurements of BL disturbance field, both mean and fluctuating components.



# Orbiter Return To Flight BLT Correlation

## RTF BLT V2 Correlation



Proposed Correlation	Correlation Equation	Ground-Based			Ground-Based + Flight		
		R	$\Delta C/C$	$\sigma_C/\bar{C}$	R	$\Delta C/C$	$\sigma_C/\bar{C}$
1	$Re_\theta/M_e \times k/\delta = C$	-0.87	1.26	19.9%	-0.88	1.25	21.2%
2	$Re_\theta/M_e \times k/\delta^* = C$	-0.90	1.08	7.3%	-0.87	1.32	34.9%
3	$Re_\theta/M_e \times (k/\delta)(T_e/T_w)^{0.16} = C$	-0.89	1.14	14.5%	-0.89	1.20	23.6%
$\Rightarrow$ 4	$Re_\theta/M_e \times (k/\delta)(H_e/H_w)^{0.30} = C$	-0.91	1.04	8.9%	-0.91	1.10	19.9%
5	$\rho_k u_k k / \mu_w = C$	-0.79	2.51	30.9%	-	-	-
$\Rightarrow$ 6	$Re_k^{0.6} \times [Re_\theta \cdot (\mu_e/\mu_k)]^{0.4} = C^*$	-0.87	1.09	14.8%	-0.84	1.30	35.0%

\* Results are for  $n = -0.6$  for all data

## Accuracy of various BLT Engineering Correlations with Orbiter RTF Data

Ref: King, R.A., Kegerise, M.A. and Berry, S.A.,  
"Proposed Protuberance Correlations for the Next Generation BLT Tool (vsn 2)",  
EG-22-07-07, March 30, 2007

## CUBRC MH-13 Wind Tunnel Model

Cassady, et al  
NASA/TP-2007-214758

Turbulent  
Wedge from  
BLT Trip

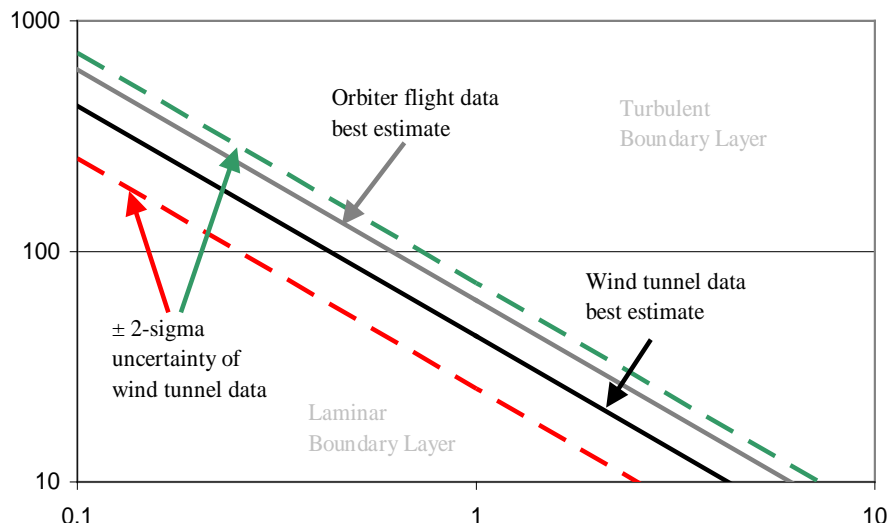
## LaRC Infrared Surface Temperature Mapping

- Wind tunnel data to support correlation acquired in Langley Mach 6 Air, Mach 10 Air, Mach 6 CF4 and CUBRC Mach 10, 14, 16
- Engineering correlations of this type achieve correlation values of  $>0.8$  on Orbiter configuration
- Better correlations are desired, but this is acceptable for providing engineering assessments and design input

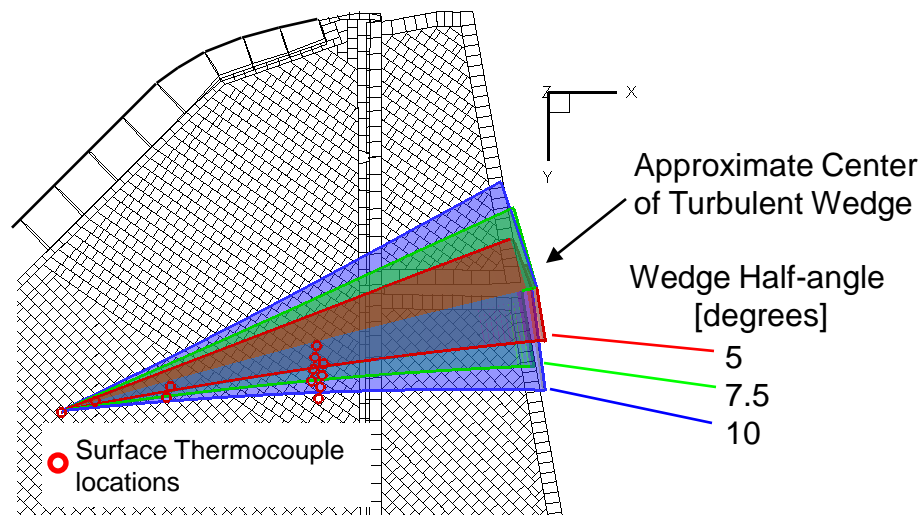


# Orbiter BLT Flight Experiment Context

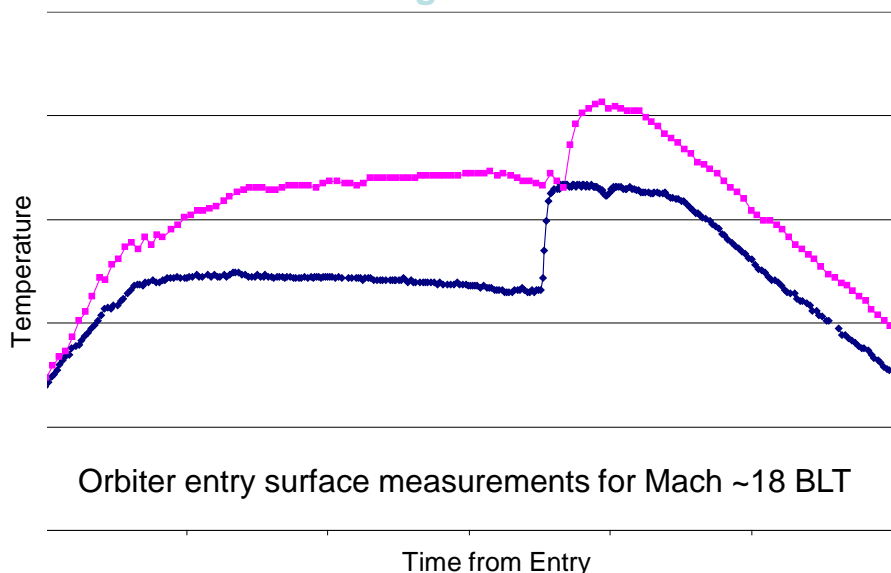
## RTF BLT V2 Correlation



## Turbulent Wedge



## Aeroheating Environments



## Comments

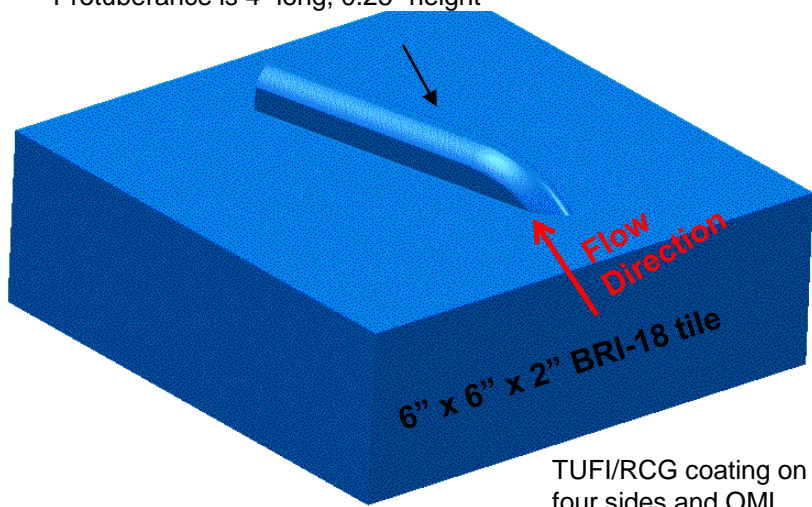
- Current Orbiter flight data BLT uncertainty is similar to correlation uncertainty (*small data sample, geometry uncertainty, etc.*)
  - Can not establish conclusions regarding wind tunnel to flight
- Orbiter assessments use 7.5 degrees for turbulent wedge
  - Could be lower, but insufficient data available
- High Mach/High Enthalpy Turbulent flow is relatively unknown regime
  - Current CFD methods based on ground data, Orbiter heating tools (e.g. XF0002) are based on limited flight data of STS 1-5 (heating uncertainty  $\approx 20$ -30%)
  - Orbiter BLT FE flight data could significantly affect tools, physical models and design/operational predictions



# OV-103 Hardware Modifications

## Protuberance Tile

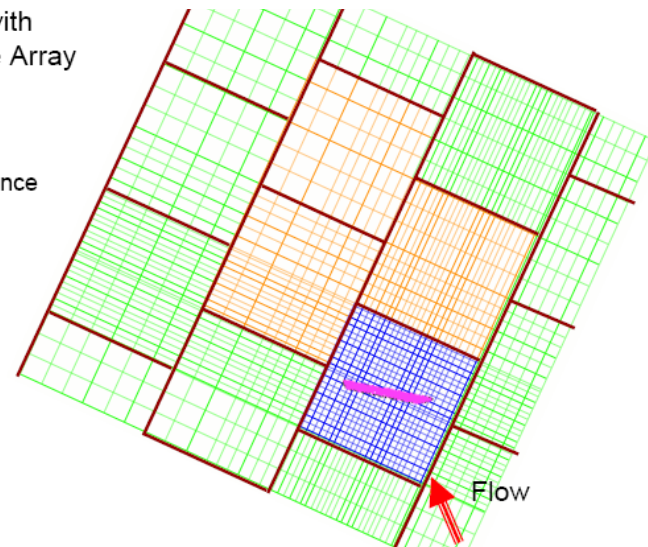
Protuberance is 4" long, 0.25" height



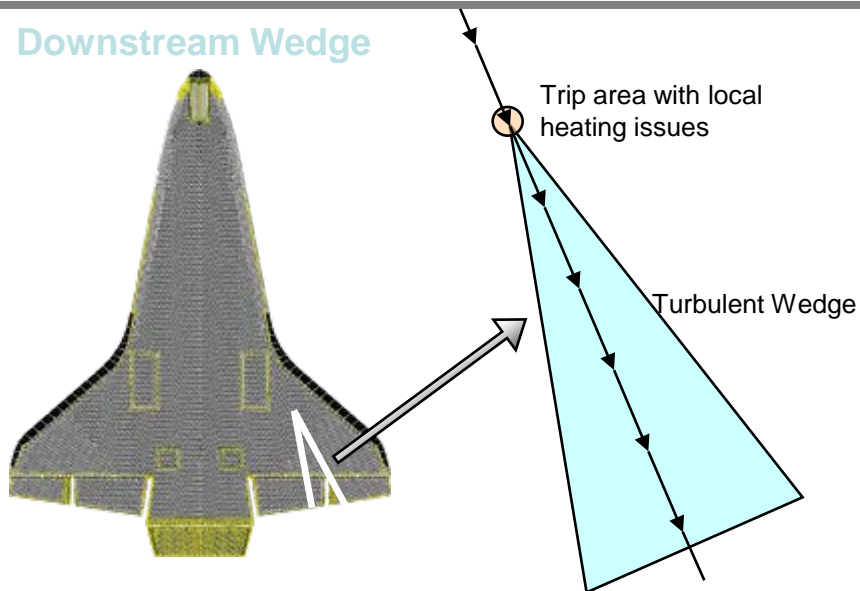
## Local Area

BLT TMM with Overlay Tile Array

- LI-900
- LI-2200
- Bri-18
- Protuberance

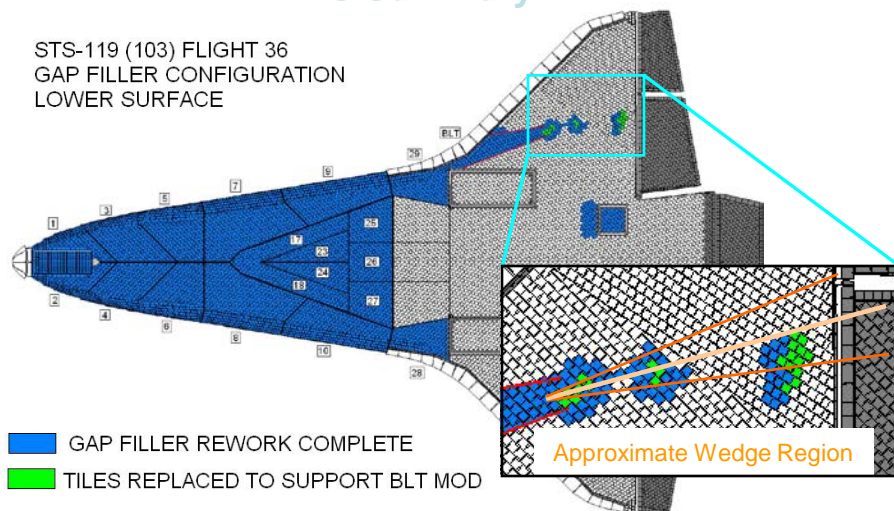


## Downstream Wedge



## TPS Summary

STS-119 (103) FLIGHT 36  
GAP FILLER CONFIGURATION  
LOWER SURFACE





**STS-119/STS-125 success criteria:** To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry

*Horvath et. al.*

**04/09 – Mission Success!** AIAA-2008-4022

**Near term goal:** Shuttle as target of opportunity to demonstrate thermal imaging capability with existing technologies during Shuttle (STS-119) boundary layer transition flight experiment

**Long term vision:** Development of new quantitative state-of-the-art imaging systems (e.g., visual, thermal, spectral) to support a variety of hypersonic flight test programs from an engineering, safety and science perspective

**Imagery from “ad hoc” flights (pre-HYTHIRM)**

**STS-121**

July 2006

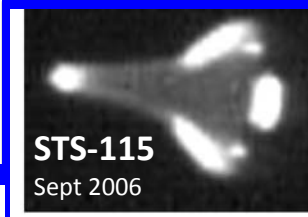


Turbulent flow from gap filler ~ Mach 13

*Horvath et. al. AIAA-2007-4267*

**STS-115**

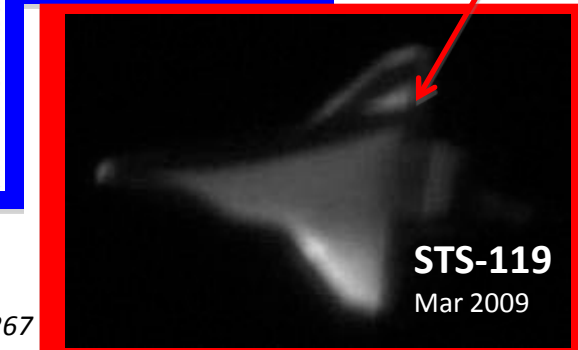
Sept 2006



**Turbulent flow from wing protuberance**

**STS-119**

Mar 2009

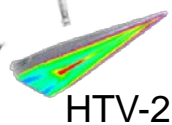


**ARES LAS**



**Orion**

**Hyfly**



**HTV-2**

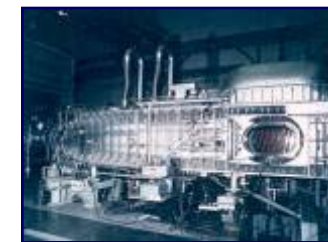
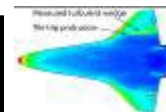
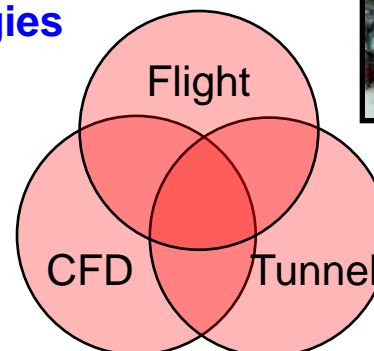
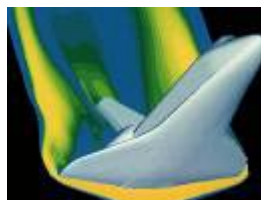
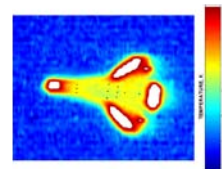
**X-37**

**X-51**

**Hyfire**

Provide tools required for an integrated test and evaluation approach in which the proper combination of modeling and simulation, ground testing, and flight testing are employed to address of future high speed hypersonic systems

## Flight Testing Technologies



## Modeling & Simulation

## Ground Test Facility Technologies

POC's: [Thomas.J.Horvath@nasa.gov](mailto:Thomas.J.Horvath@nasa.gov) (PI) and [Paul.W.Krasa@nasa.gov](mailto:Paul.W.Krasa@nasa.gov) (PM)

Sponsors: NASA JSC SSPO; NESC, ARMD

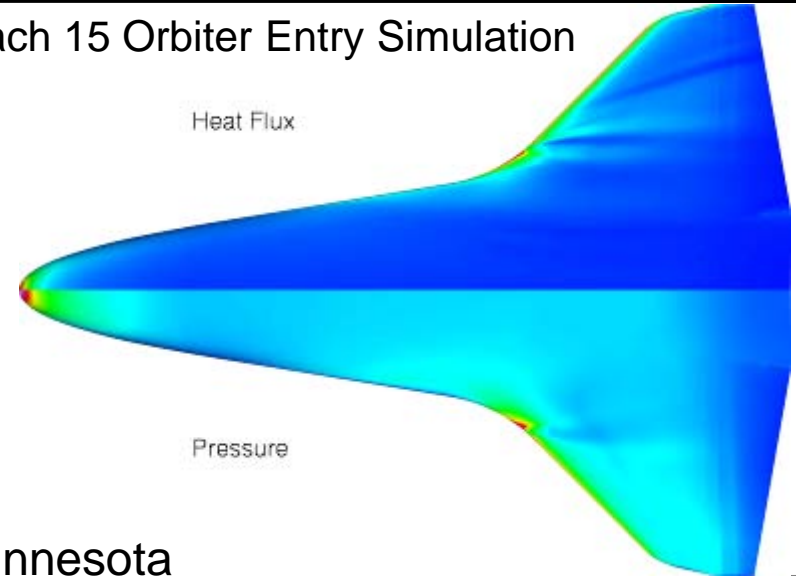


# Orbiter Entry BLT Stability Modeling

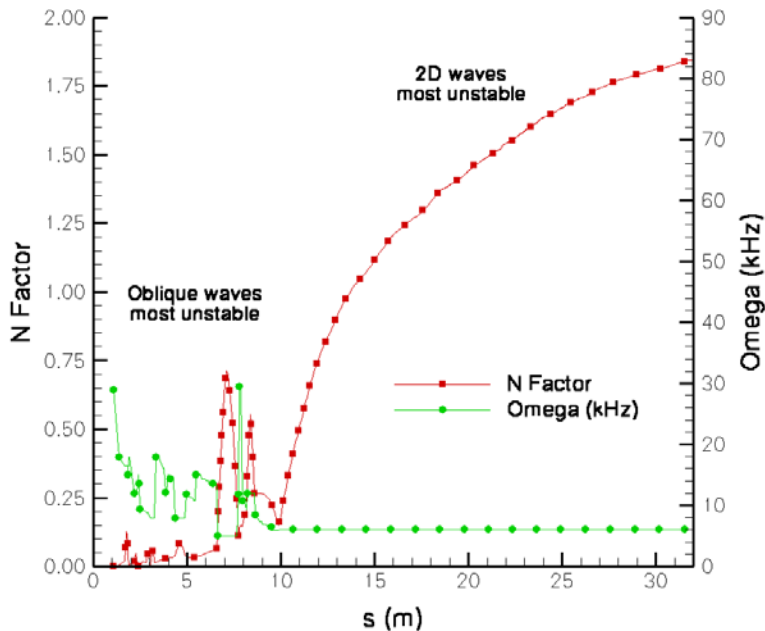
Graham V. Candler  
Heath B. Johnson

- 128 million element Orbiter grid provided by NASA
- Solved using U of MN US3D finite-volume solver with 1400 cores
- 5-species air finite-rate thermochemistry
- Centerline flow solution extracted and analyzed using Parabolized Stability Equations in STABL

## Mach 15 Orbiter Entry Simulation

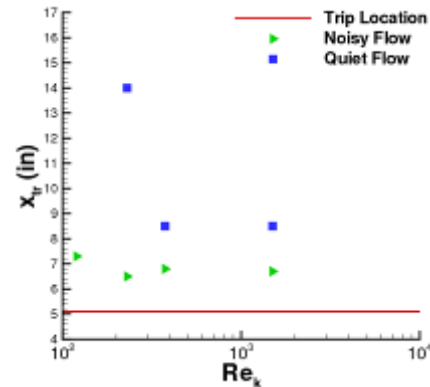
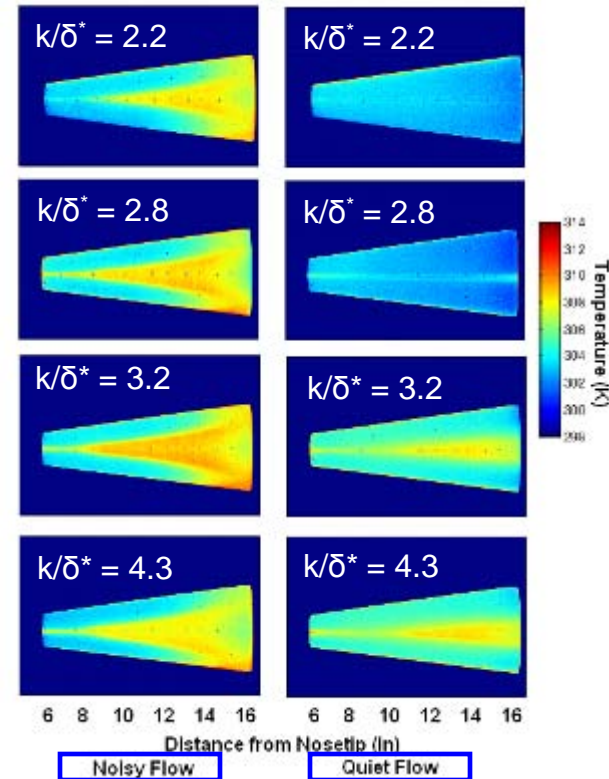


University of Minnesota

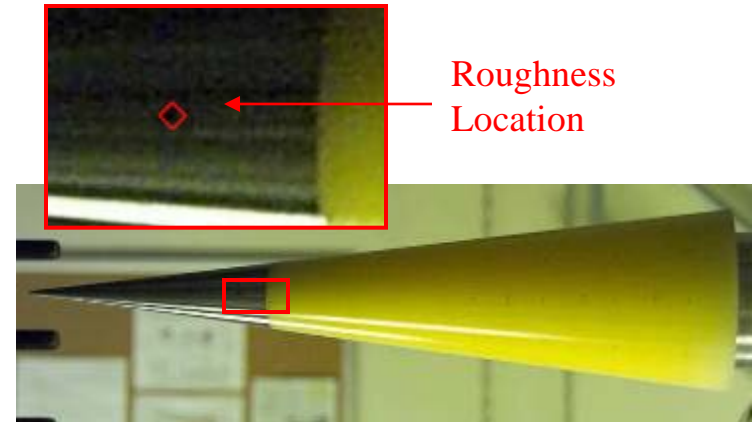


- Demonstrates it is possible to generate stability-quality CFD solutions for Shuttle
- Initial results show N-factor of nearly 2 at rear of shuttle
- Oblique waves dominant near the nose but 2D waves reach higher N
- Currently a centerline flow analysis
- Future results will include off-axis 3D effects in the stability analysis

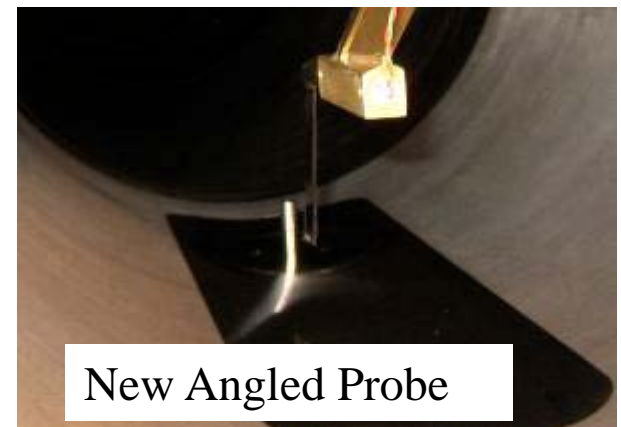
## Effect of Tunnel Noise on Roughness-Induced Transition for a Slender Cone at Mach 6



7-deg. half-angle cone,  
0.047-in. nose radius, about 3E6/ft.



Hot Wire in Wake of  
Isolated Roughness



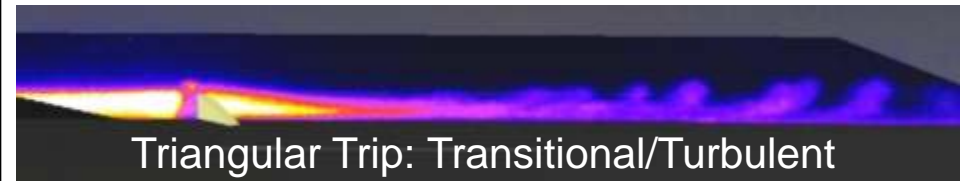
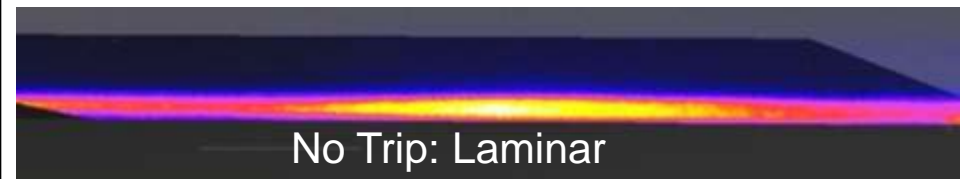
Ref: Casper et al., AIAA Paper 2008-4291

- Effective trips under noisy flow are not always effective under quiet flow
- When transition did occur under quiet flow, it was always delayed

## Overview

- Nitric Oxide Planar Laser-Induced Fluorescence (NO PLIF)
  - Pioneered at Stanford in 80's and 90's (Hanson)
- Laser/Camera system visualizes slices of flow
- Quantitative measurements
  - Velocity, temperature
- Used in 31" Mach 10 Wind Tunnel
- Primarily Supported by NASA Fundamental Aero Program, Hypersonics Project

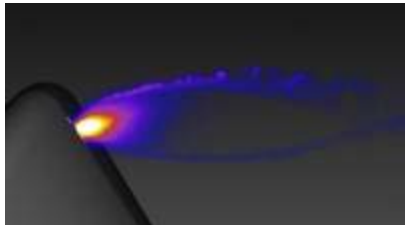
## Recent Applications: Transition Studies



Danehy et al., AIAA Paper 2007-0536

- Triangular trip simulates orbiter gap filler
- NO seeds BL fluid, marks flow structures

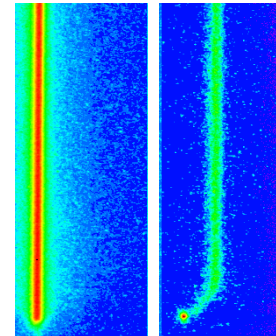
## Recent Applications: RCS Jet Imaging



- Measure shape, transition, trajectory, velocity, of RCS jets for both Aero and Aeroheating applications

Inman et al., AIAA Journal (accepted; in press).  
Danehy et al., Journal of Spacecraft and Rockets,  
vol. 46m p. 93-102 (2009).

## Future Capabilities

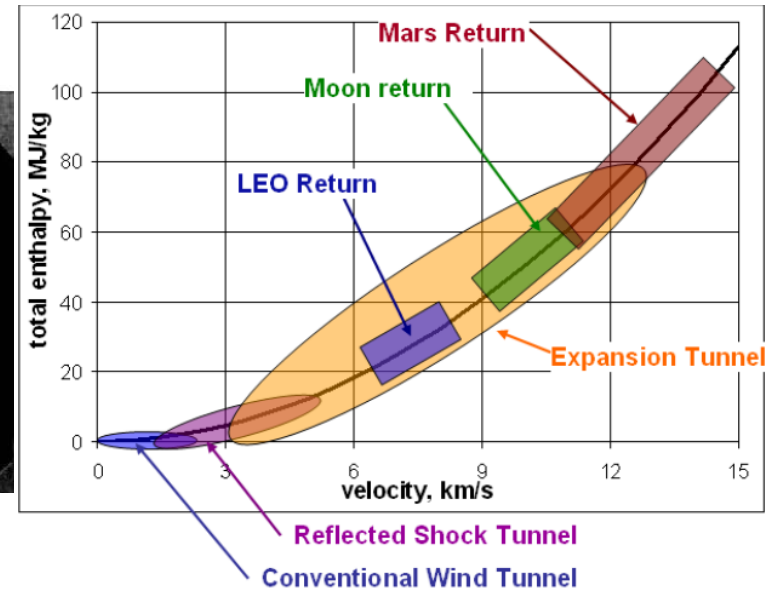
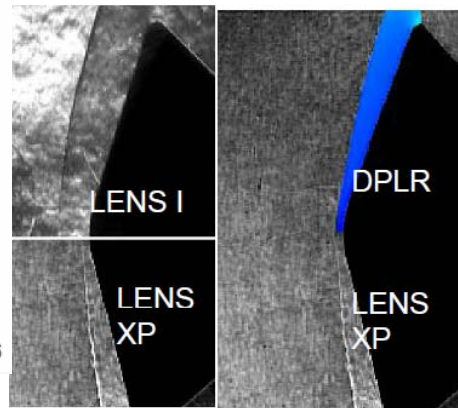
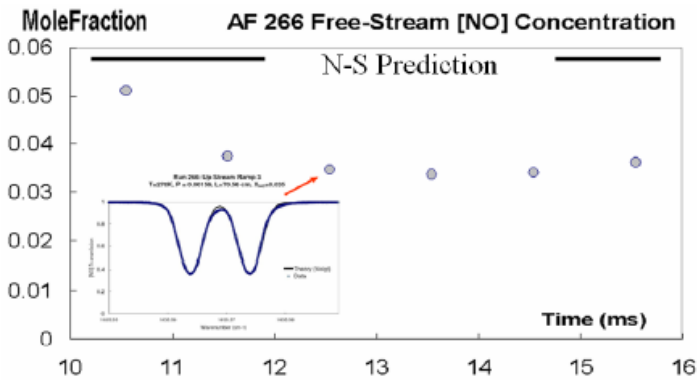


Delay= 0ns      500 ns

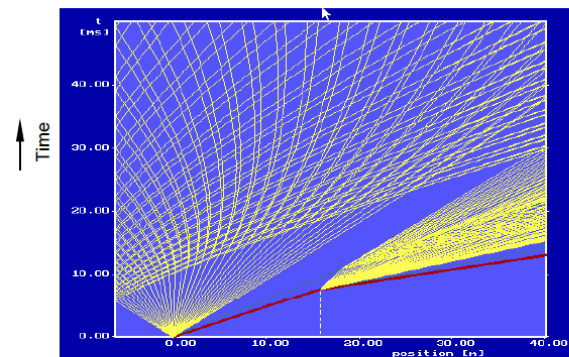
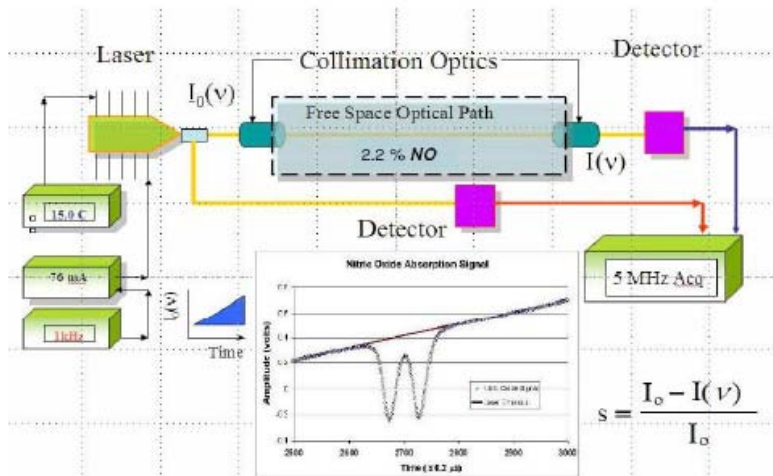
Velocity Measurement  
 $velocity = \frac{distance}{time}$

Danehy et al, AIAA Journal  
v.41, n.2, p. 263-271 (2003).

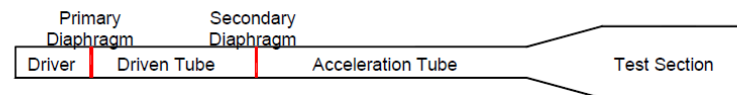
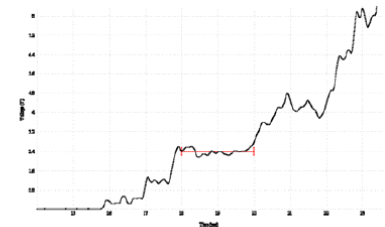
- High speed imaging, velocimetry:
  - MHz Frame Rate Laser/Camera system (NRA with Ohio State)
- Temperature measurement



### Measurements of NO in Freestream and Shock Layers Employing Tunable Diode Laser Spectroscopy



2ms Test Time for 10 MJ/kg



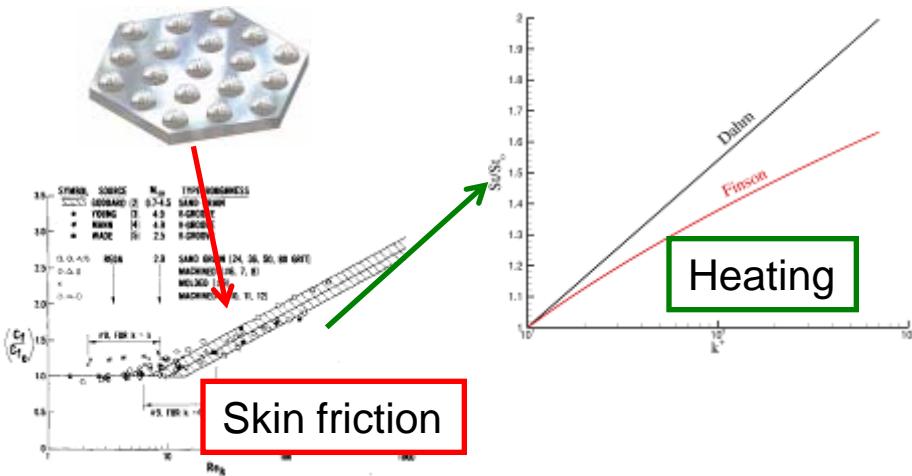
Ref: Wadhams, et al AIAA 2007-551,  
Holden et al, AIAA 2008-2505,  
MacLean et al, AIAA 2007-121



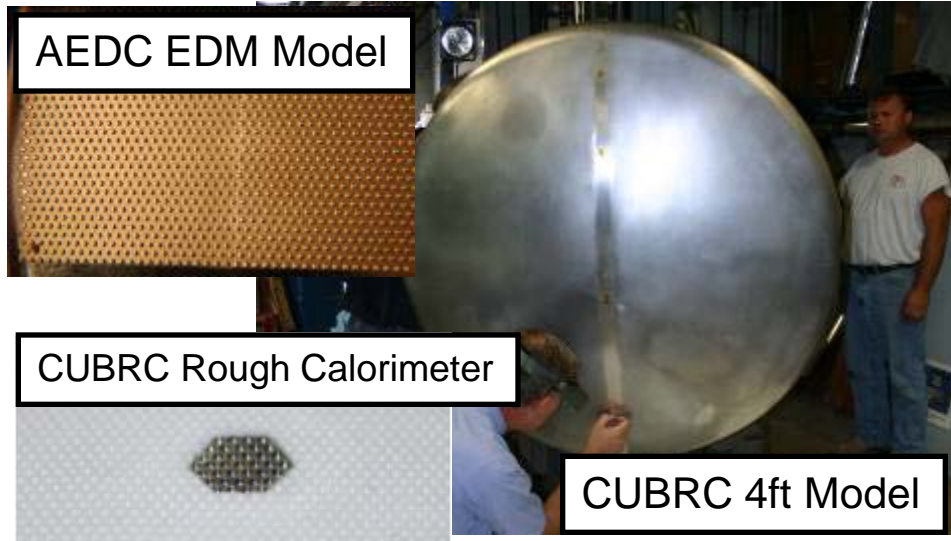
# Roughness and Heating Augmentation

Adam Amar and Brandon Oliver / NASA JSC

Geometry/Spacing/Height



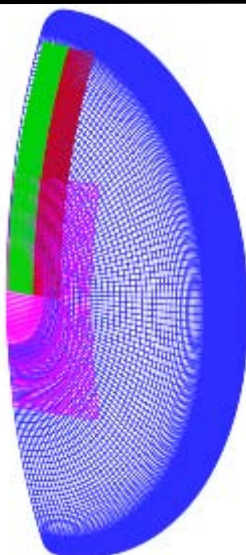
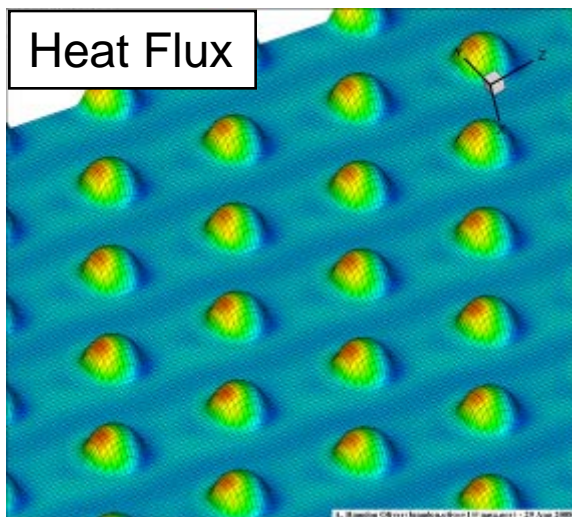
AEDC EDM Model



CUBRC Rough Calorimeter

CUBRC 4ft Model

Heat Flux



CFD corroborates wind tunnel trend

Orion/CEV testing

- Agrees with historic data
- Shows existing correlations are reasonable

Model will be a function of:

- Roughness geometry
- Smooth wall boundary layer properties

Forward work

- Examine blowing effects on roughness
- Get augmentation data for Avcoat patterns

# STS-119 Launch Photo



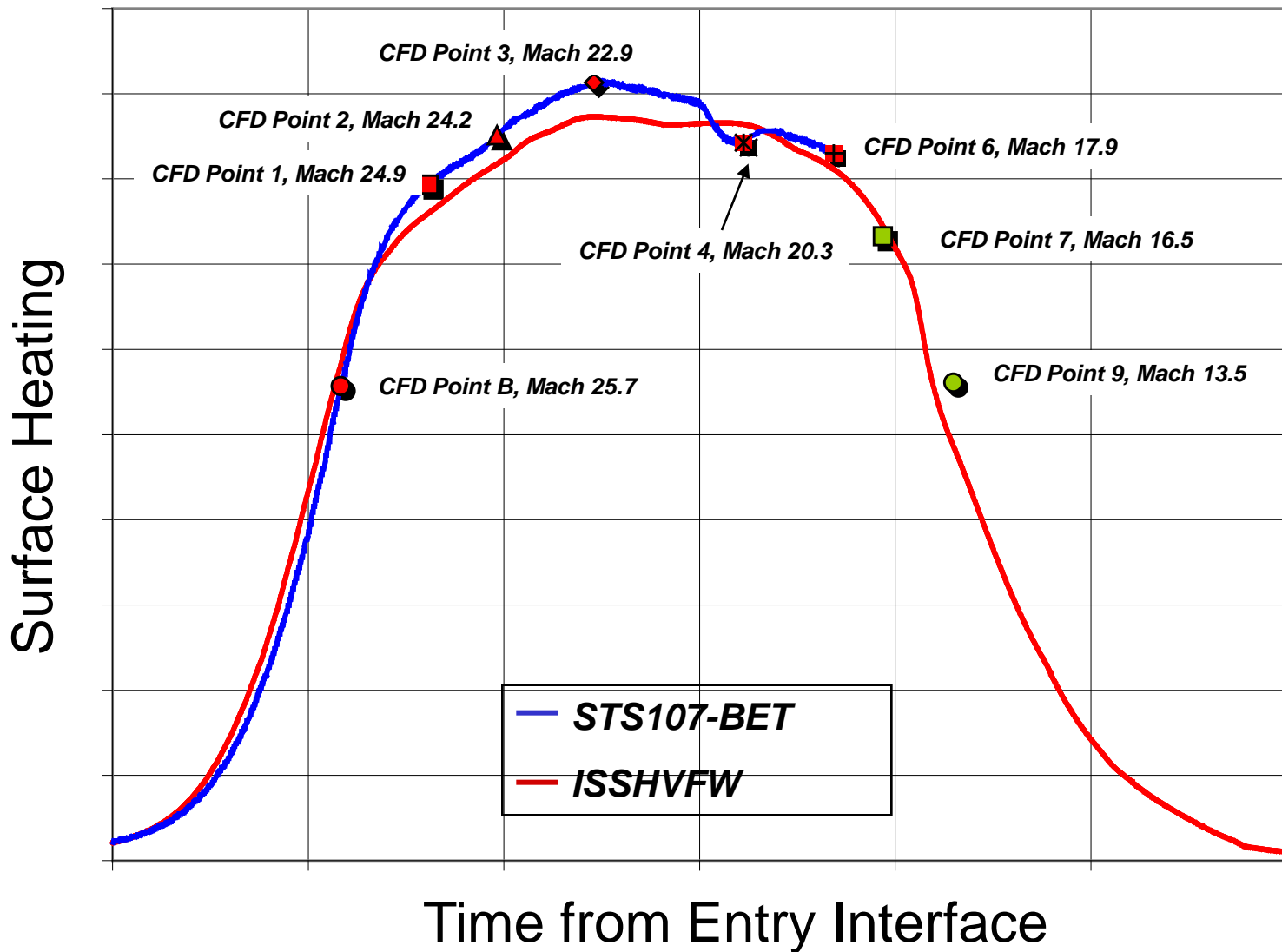
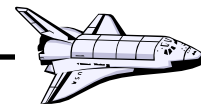
*Ryan R. Smith*

STS-119, March 15, 2009

# Back-up

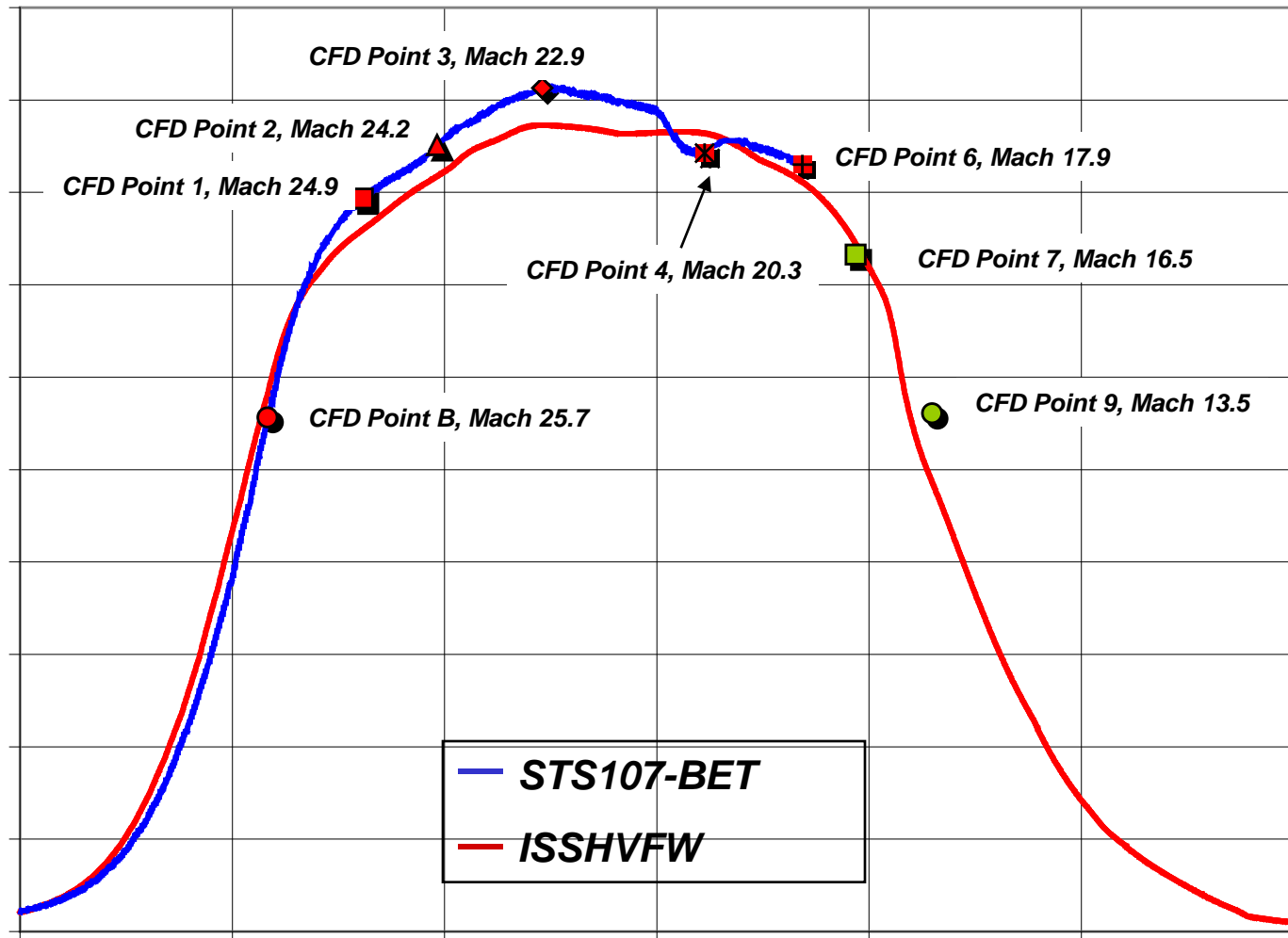
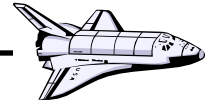


# CFD Repository



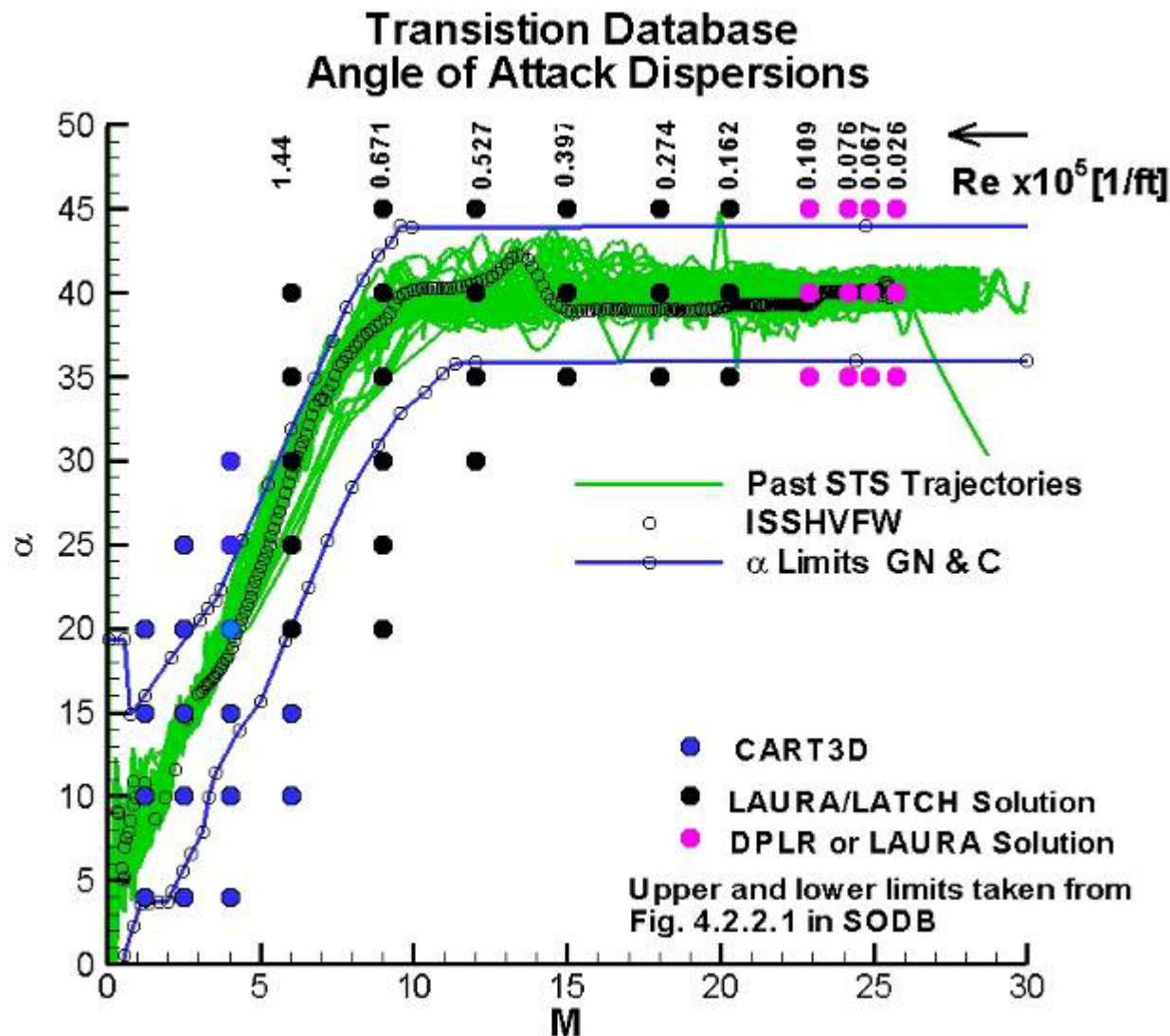
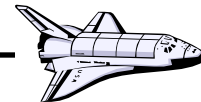


# CFD Repository





# Boundary Layer Properties DB





# Simplified Cavity from Point Cloud

